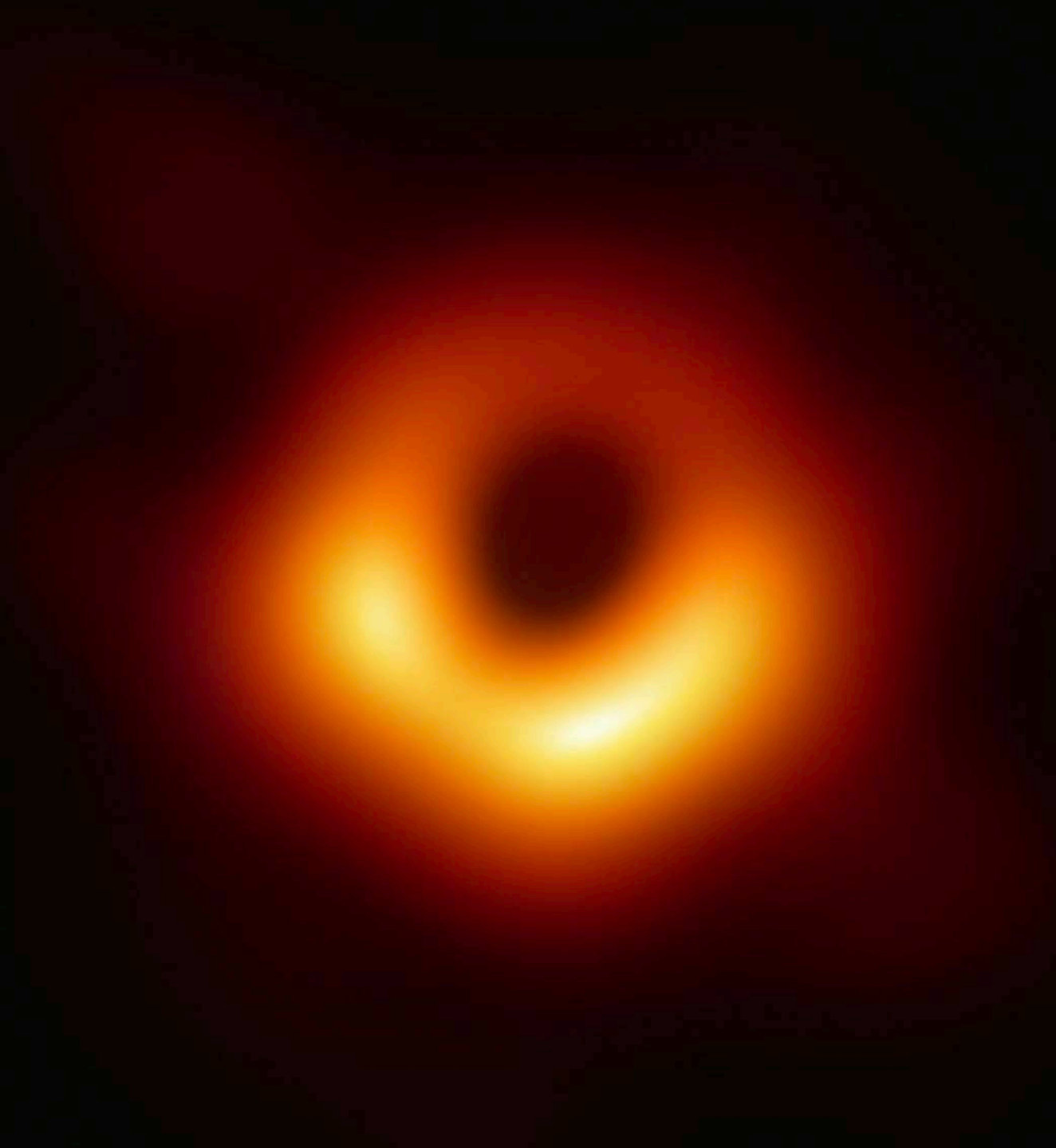
15: Peering into the black hole

Physics 17: Black Holes and Extreme Astrophysics



In case you are interested…

"The Event Horizon Telescope: Imaging a Black Hole Through Global Collaboration"

Event Horizon Telescope founding director, Dr. Shep Doeleman

Monday, November 9, 2020

4:00PM – 5:30PM ET (1:00PM PT)

https://bostonchildrens.zoom.us/webinar/register/WN_3pC8yM2lTRSgMDwimZrtCg

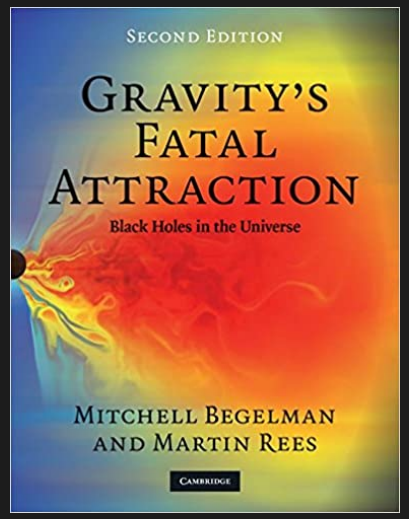
Goals

- Build a theoretical image of the gas accreting onto a black hole
- Revise emission mechanisms at work around black holes
- Find out how we can build a telescope with the ability to resolve the event horizon
- See and interpret the first picture of a black hole

Reprise

- Light rays are bent around massive objects (gravitational lensing, L12.17)
- No light and no information can escape from inside the event horizon of a black hole (L6.8)
- Light, X-rays and radio waves are emitted by heated gas around black holes (L7.15)
- When we observe light emitted from gas in orbit around the black hole, the observed wavelength is shifted by Doppler shifts and gravitational redshifts (L14.17)

Reading

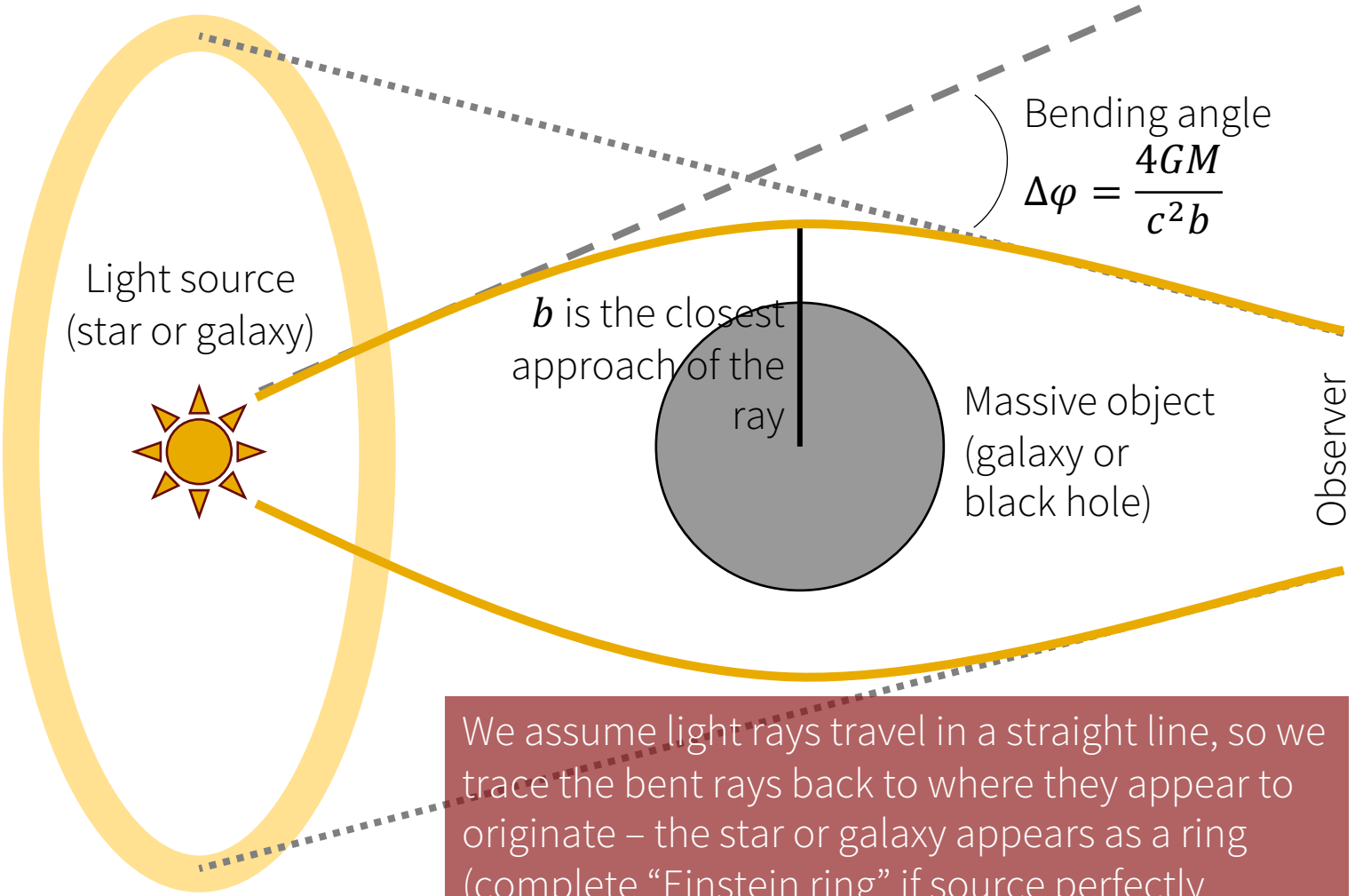


Begelman & Rees

- Radio astronomy and interferometry (p128-131)

Bigl L12.17

Gravitational Lensing



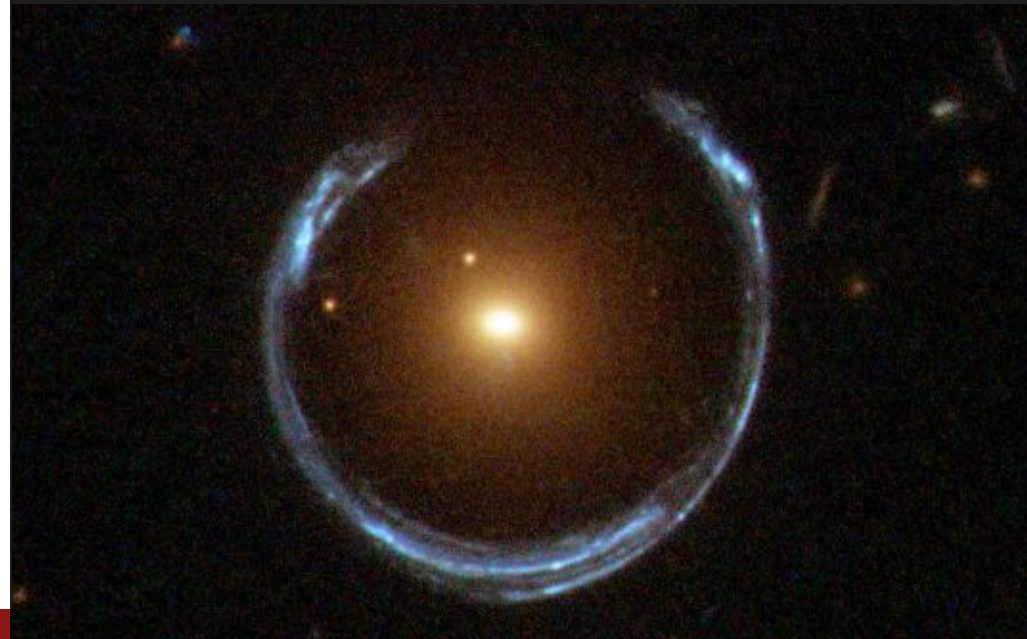
We assume light rays travel in a straight line, so we trace the bent rays back to where they appear to originate – the star or galaxy appears as a ring (complete "Einstein ring" if source perfectly aligned behind lens, otherwise a broken ring)

In general relativity, gravity is due to the curvature of spacetime

Light follows geodesics (shortest path between two points – straight lines in flat space)

Geodesics bend in curved spacetime, towards a massive object, which we experience as gravity

Light is affected by gravity and is bent towards massive objects



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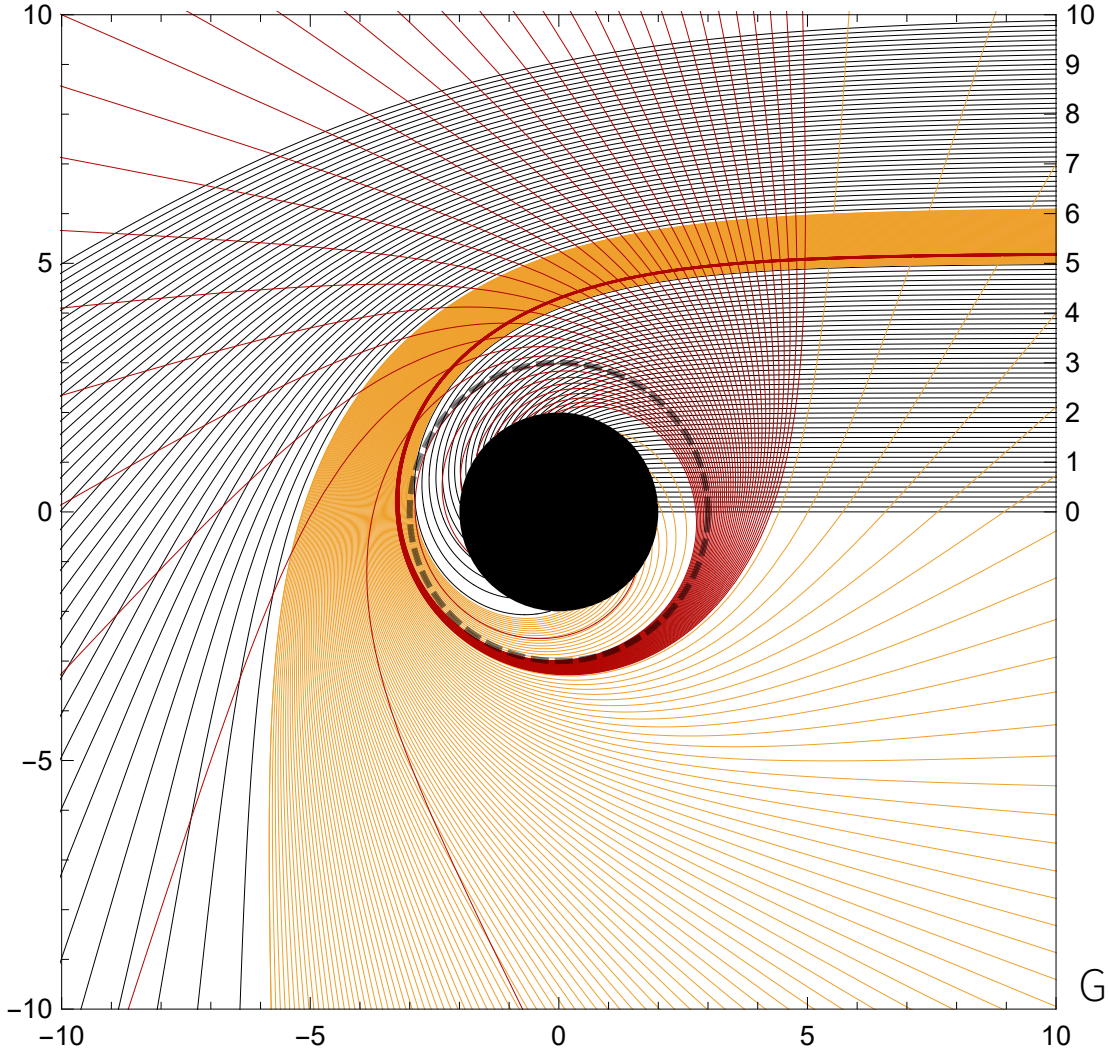
Light in orbit!



Black rays are bent by black hole

Rays can stay in orbit around the photon ring (dashed line)

Red rays travel around black hole

Gralla et al. 2019

In general relativity, light can travel in a circular orbit around the black hole at one specific radius – the photon orbit, or photon ring

The photon orbit is unstable — need to be exactly at the correct radius to stay in orbit indefinitely

Light rays or photons slightly off the orbit will complete many orbits of the black hole before leaving the orbit and either escaping or falling in

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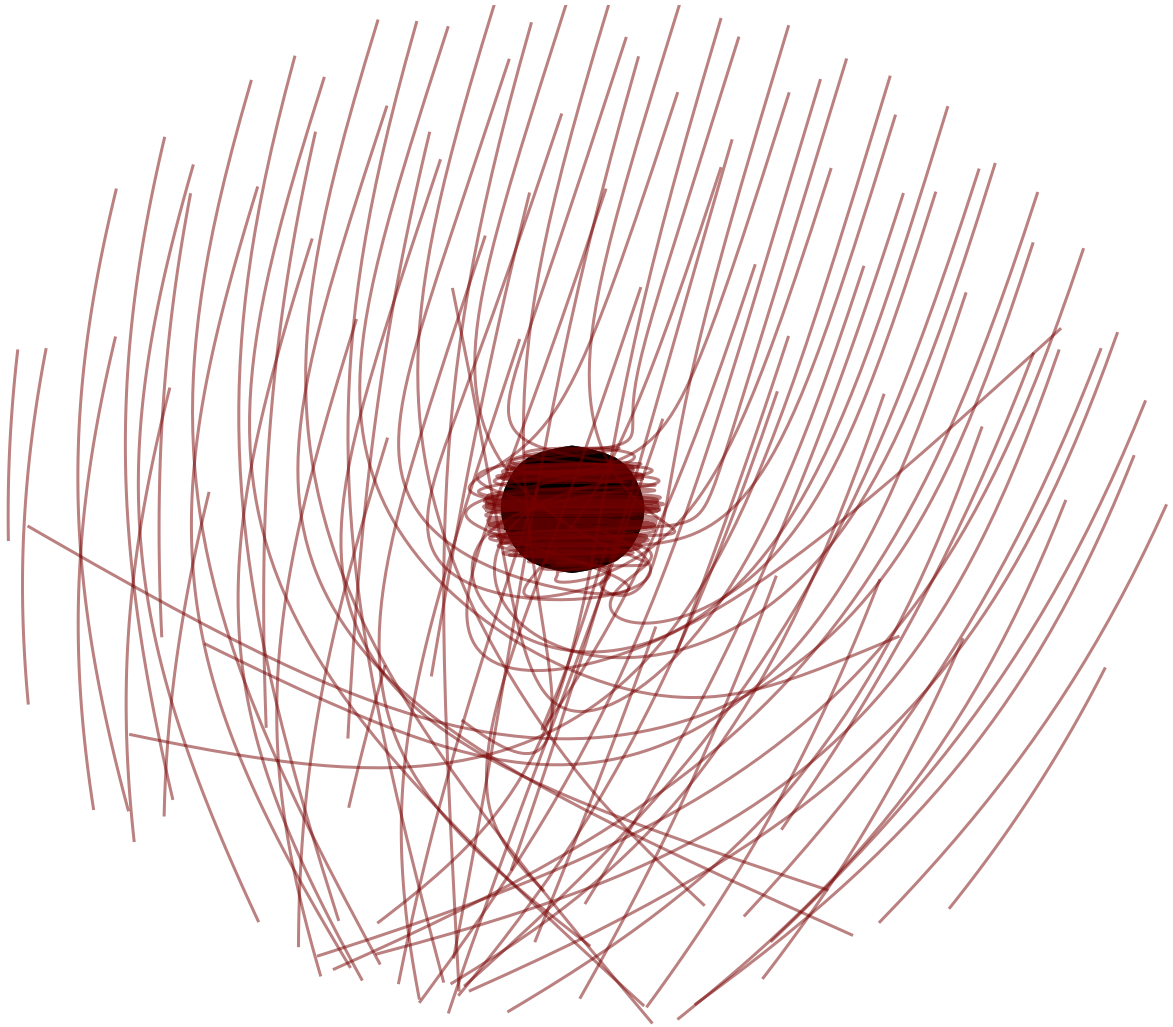
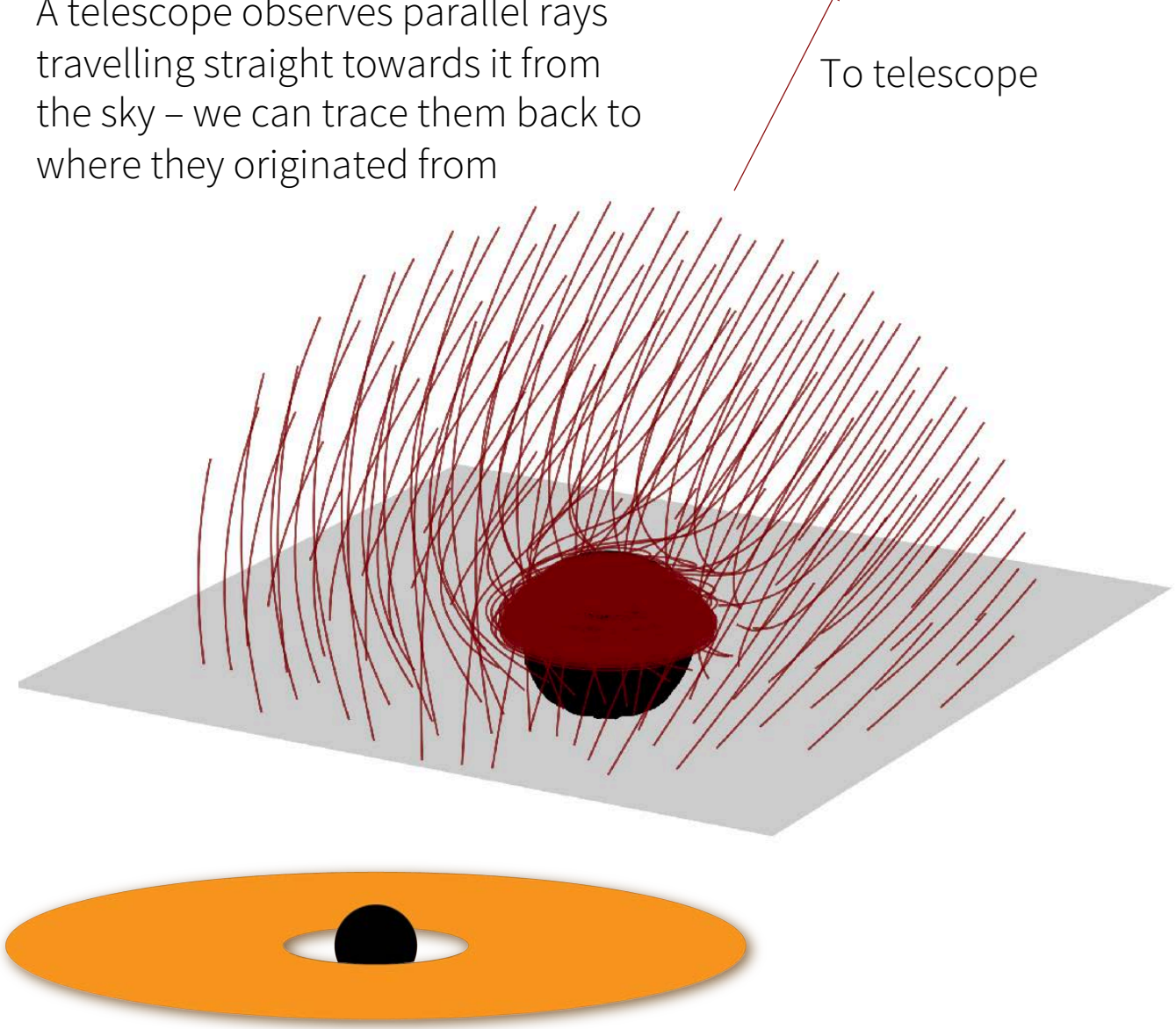
Light Bending around a Black Hole



- Light rays are bent towards and around the black hole
- Light rays can enter the photon orbit and complete many revolutions of the black hole
- When the black hole is spinning, frame dragging pulls many more
- Rays that pass through the event horizon are lost into the black hole

Imaging the accretion disk

A telescope observes parallel rays travelling straight towards it from the sky – we can trace them back to where they originated from



Imagine building the ultimate telescope which can resolve an image of the accretion disk around a black hole.

We are observing a flat accretion disk close to edge-on

Consider how the light emitted from the accretion disk bends around the black hole, and the different ways light can reach the telescope from the accretion disk?

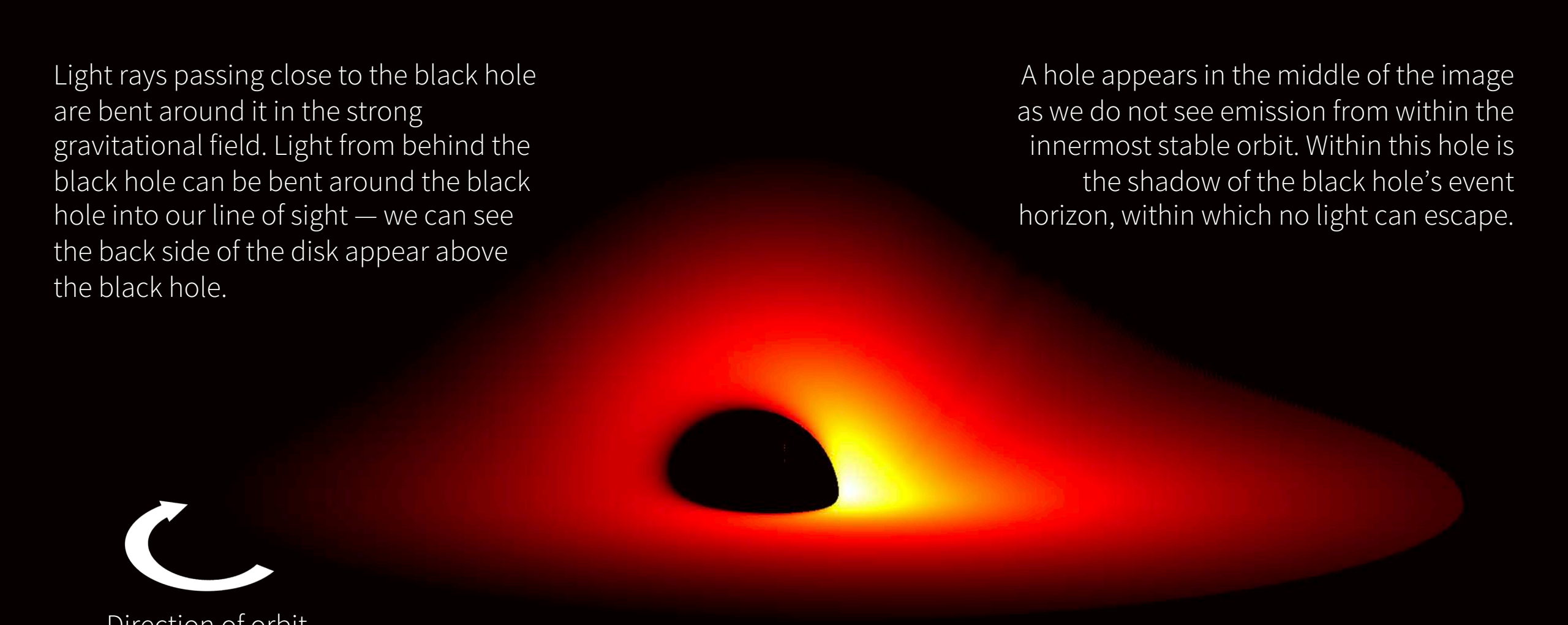
a. How will the shape of the disk appear in the telescope?

b. Can we see the light emitted from parts of the disk behind the black hole?

c. How bright will different parts of the disk appear?

Light rays passing close to the black hole are bent around it in the strong gravitational field. Light from behind the black hole can be bent around the black hole into our line of sight — we can see the back side of the disk appear above the black hole.

A hole appears in the middle of the image as we do not see emission from within the innermost stable orbit. Within this hole is the shadow of the black hole's event horizon, within which no light can escape.



Direction of orbit

Light emitted closer to the black hole experiences stronger gravitational redshifts. The parts of the disk closest to the black hole appear dimmer and redder.

*we can't directly resolve this image, but we can measure these from the energy shifts of X-rays (L14.17)

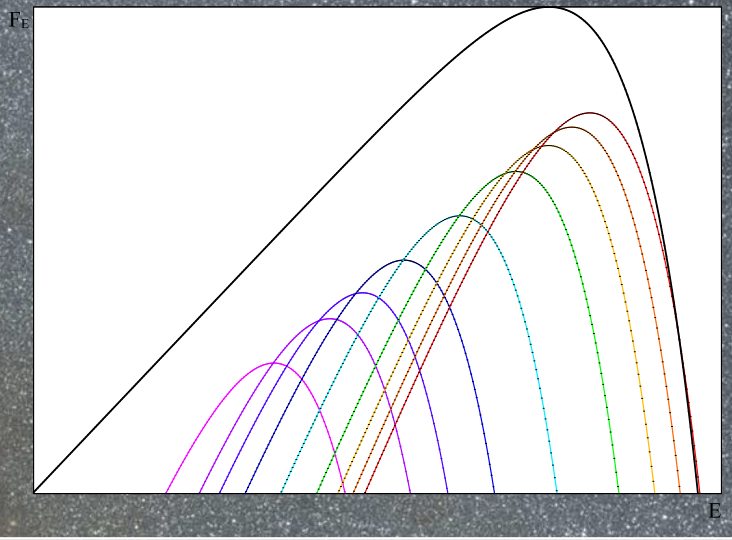
The gas in the accretion disk travels in orbit around the black hole. The light emitted is Doppler shifted. The side of the disk travelling towards us appears brighter and the light appears shifted to shorter wavelengths (bluer colors). The side of the disc travelling away from us is dimmer and shifted to longer wavelengths (redder colors).

L14.15

The Accretion Disk

Gas spiraling into the black hole through the accretion disk is heated by friction, generated by magnetic fields that are anchored to parts of the disk orbiting at different speeds

Temperature increases at smaller radii and hot gas emits black body radiation. Around stellar mass black holes, peaks at X-ray wavelengths. Disks around supermassive black holes are cooler and the emission peaks at UV wavelengths



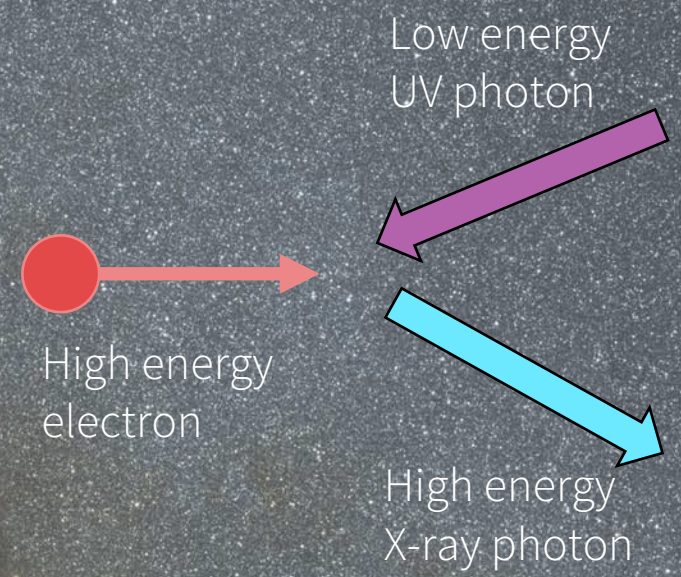
L14.16

The Corona

Electrons accelerated to high velocities (kinetic energy) in magnetic field close to black hole

X-rays produced by Compton Scattering

Low energy photons (e.g. UV light emitted from hot accretion disk) hit high energy electrons. Energy transferred from electron to photon, increasing photon energy and producing X-rays

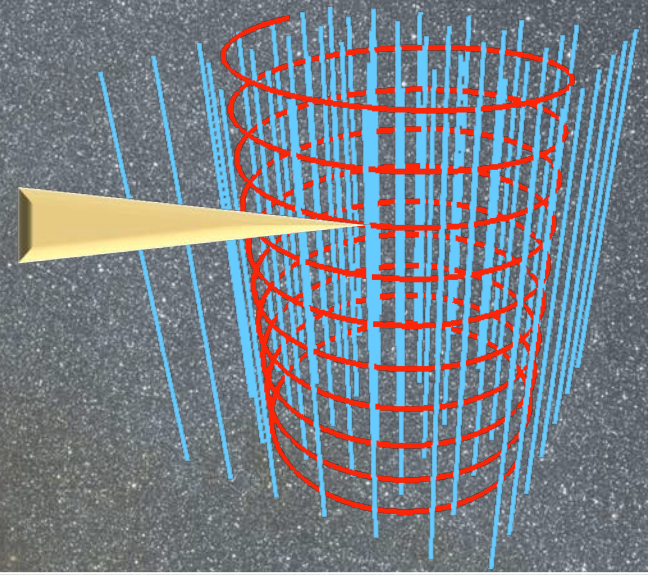


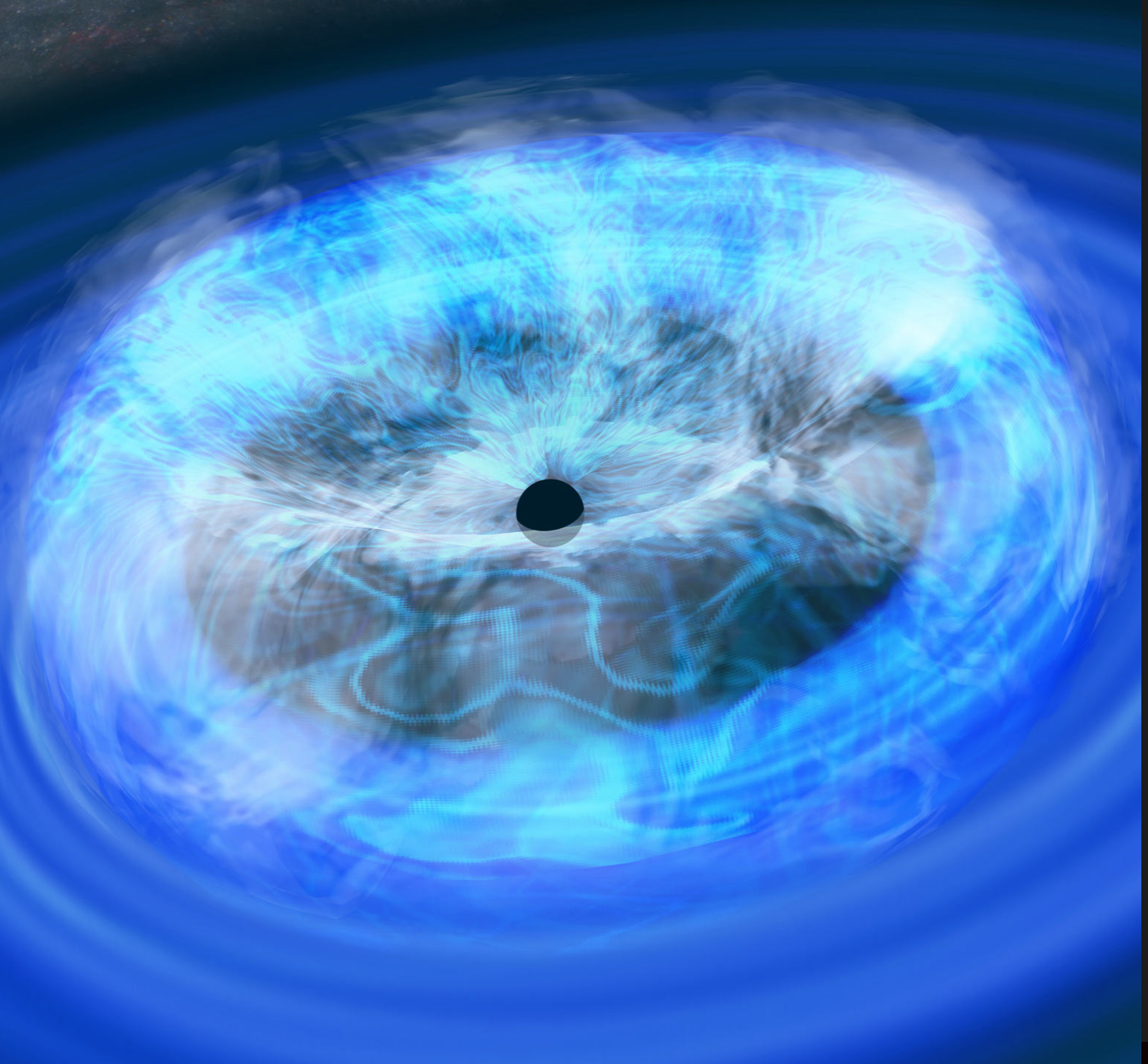
The Jet

Particles accelerated close to speed of light by magnetic fields passing through rotating accretion disk and black hole. Can extract energy from the spin of the black hole.

Electrons spiral around magnetic field lines

When electrons move in a circle, close to the speed of light, they emit a beam of **synchrotron radiation** in their direction of motion (radio, sub-mm and in extreme cases, X-rays and gamma rays)





When gas falls towards a black hole at **low rate** (e.g. onto Sgr A* in the Galactic Center), a flat accretion disk is **not** formed

The low density of the gas means it cannot cool. Thermal pressure stops it collapsing into a disk

Forms a **radiatively inefficient accretion flow**

Hot, low density, threaded by magnetic fields

Emits radio and sub-mm **synchrotron radiation**

Dark shadow in the center due to the event horizon from which no light escapes

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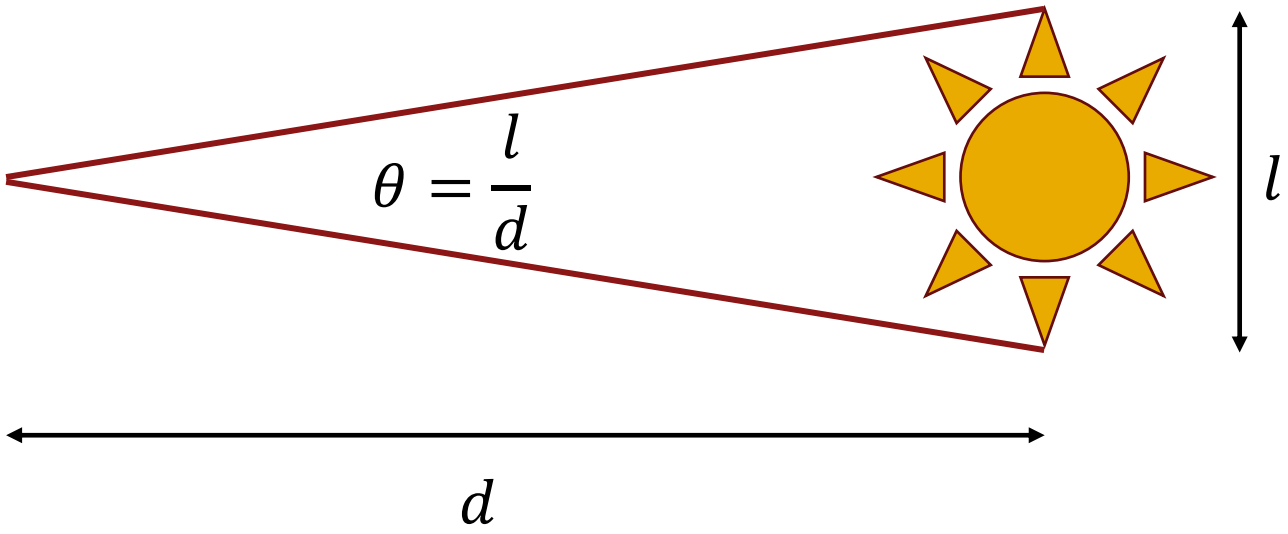
How big does a black hole appear?

Describe the apparent size of an object in the sky (length l, distance d) by its angular size, θ



$\theta = \frac{l}{d}$ is valid for small angles, and measured in radians

QaD

Mass	r_{Sch}	Distance	Size
Sgr A*	$4\times10^6 M_\odot$	10^{10} m	10^4 ly	20 μas
M87	$2\times10^9 M_\odot$	10^{13} m	10^7 ly	20 μas

Often measure angular sizes in arcminutes (1 minute is a 60th of a degree) or arcseconds (1 second is a 60th of a minute)

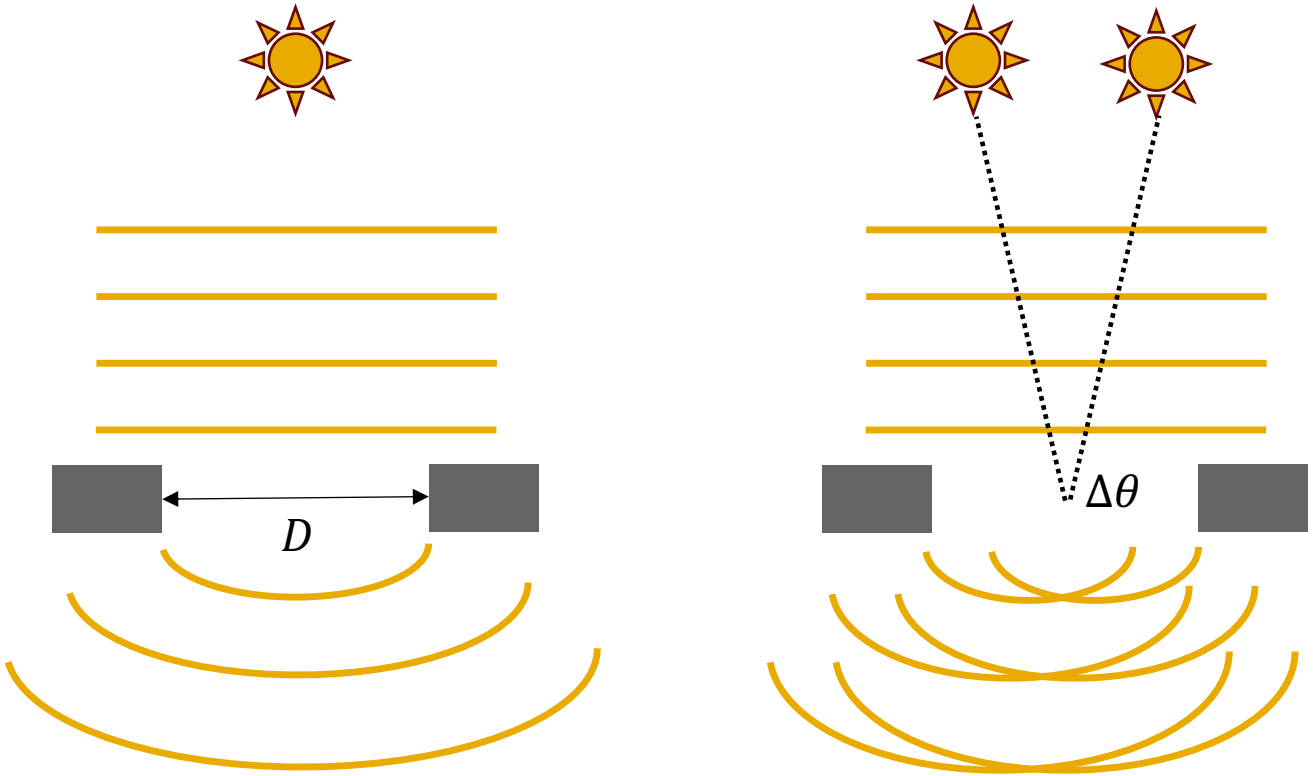
Angular size of moon ~0.5 deg

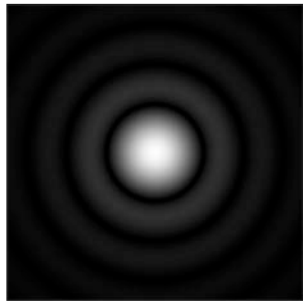
Nearest supermassive black hole is Sgr A* in the Galactic Center – event horizon is **20 μas** — equivalent to observing an apple on the surface of the moon

Supermassive black hole in M87 is 1000x further away, but 1000x larger so appears with approximately the same angular size

QaD

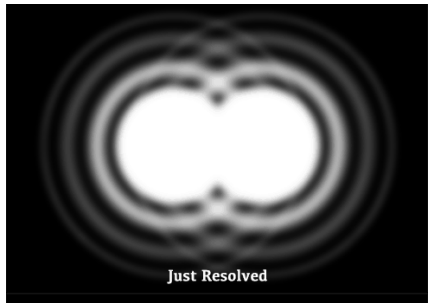
Resolution of a telescope





Resolution

$$\Delta\theta_{\min} \sim \frac{\lambda}{D}$$



The resolution is the closest two points of light can be before they appear to be a single point, or the smallest scale on which structure can be seen in an image

The light wave from a point (e.g. a star) undergoes diffraction as it enters the telescope, due to the finite size of the telescope — the point appears as a disk

Diffraction depends upon the wavelength of the light (λ) the size of the opening the wave passes through (D), and is greater for a smaller opening — **large telescopes can resolve smaller points than small telescopes**

The image of a point is also blurred by motion of the Earth's atmosphere, but the diffraction limit is the upper limit on the resolution of a telescope with n atmosphere

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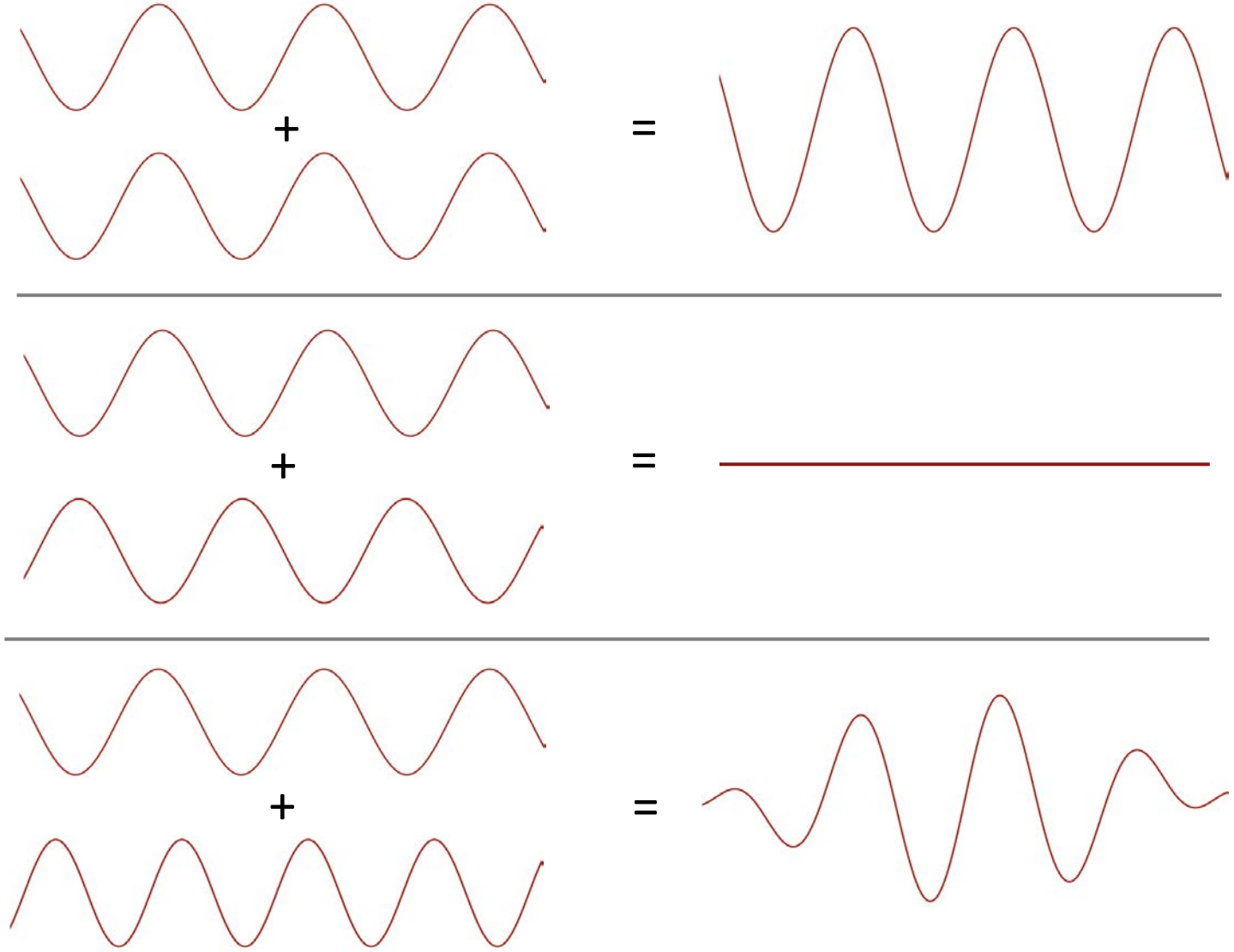
Interference of waves

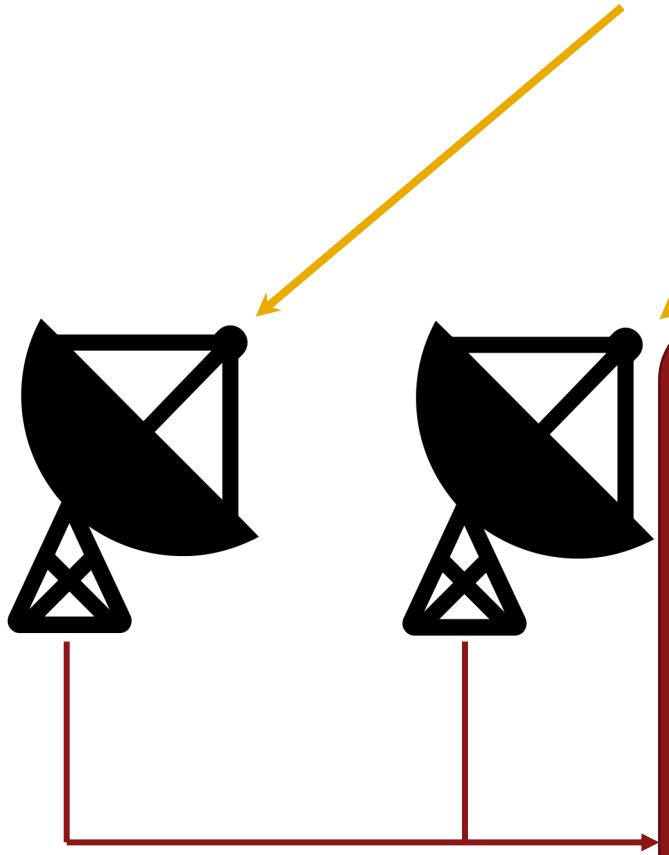


Light can be considered as a wave

When two waves add together, they interfere

- Constructive interference – the peak of one wave adds to the peak of another to produce high amplitude
- Destructive interference – the peak of one wave adds to the trough of another to produce low amplitude

Interferometry



Combine waves in the **correlator** to produce interference pattern

Frequency of radio waves is low enough to record the waveform and combine/interfere electronically

Very Long Baseline Interferometry (VLBI): telescopes can be far apart (around the World). Waveform data sent by fiber optic or radio transmitter, or stored on disks which are transported.

Can produce interference between the waves received by 2 or more telescopes

Wave peaks will be offset in light or radio waves received from different positions on the sky

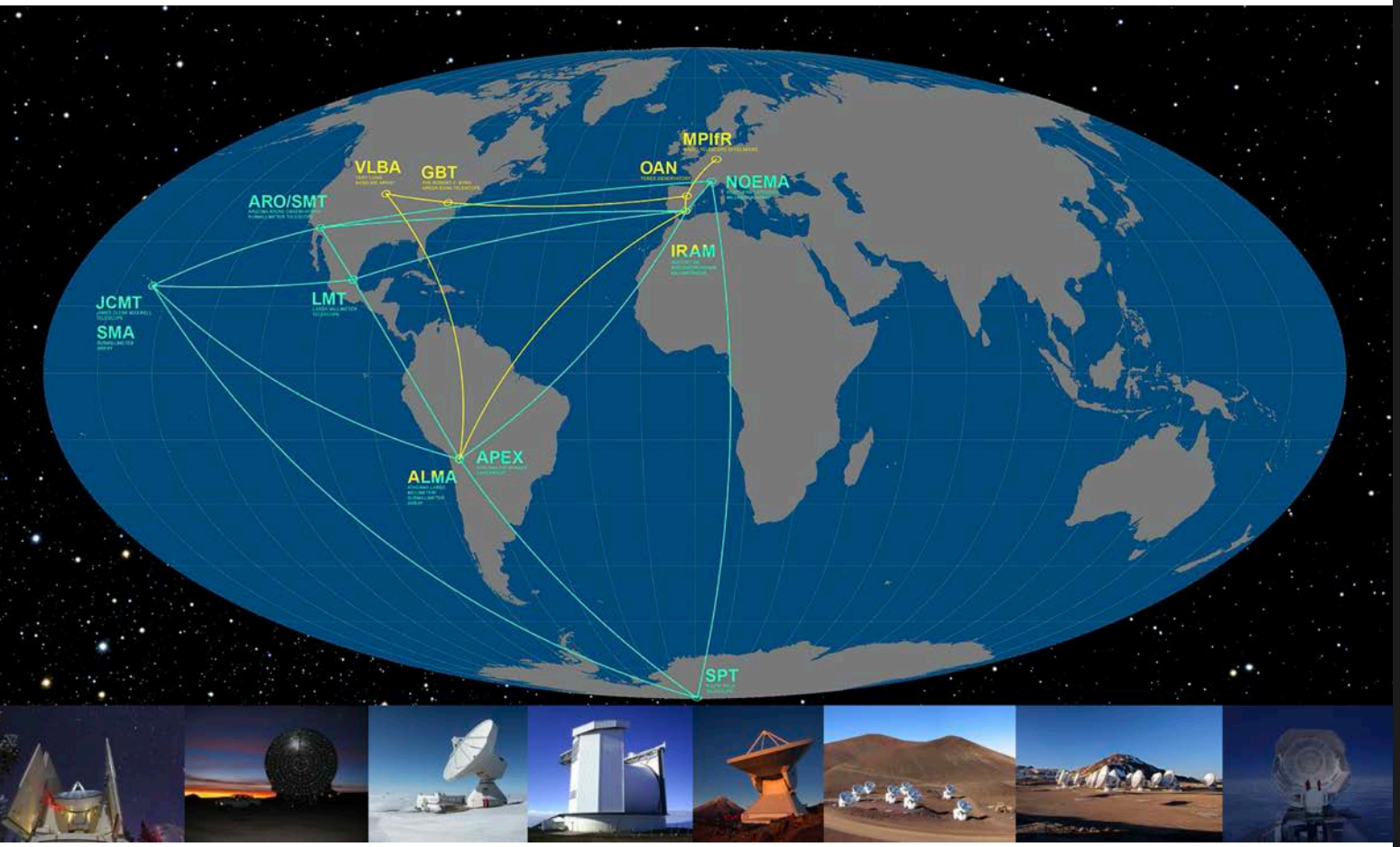
Interference is sensitive to the separation of peaks between the waves, and to the separation of sources in the sky

The resolution of the interference depends not on the diameter of a single telescope, but the separation between the telescopes

$$\Delta\theta_{\min} \sim \frac{\lambda}{d}$$

The Very Large Array (VLA)

The Event Horizon Telescope



To achieve the spatial resolution required to resolve the event horizon of supermassive black holes, the Event Horizon Telescope combines simultaneous observations from sub-mm (short wavelength radio) telescopes around the world

Effective size of telescope is the diameter of the Earth

Each telescope has an atomic clock to record the waveform against an accurate time standard

Waveforms are stored on hard disks and flown to Cambridge MA and Bonn, Germany, to combine

Advanced computer algorithms reconstruct the image from the interference pattern of the waves

Sagittarius A* (Sgr A*)

- Supermassive black hole in the Galactic Center
- Event Horizon Telescope observations upcoming!

Messier 87 (M87)

- Giant elliptical galaxy, ~100x larger than Milky Way
- Supermassive black hole
- 54 million light years away
- Jet launched by black hole in nucleus, extends 5,000 ly
- Observed by the Event Horizon Telescope in 2017 (and further observations planned)

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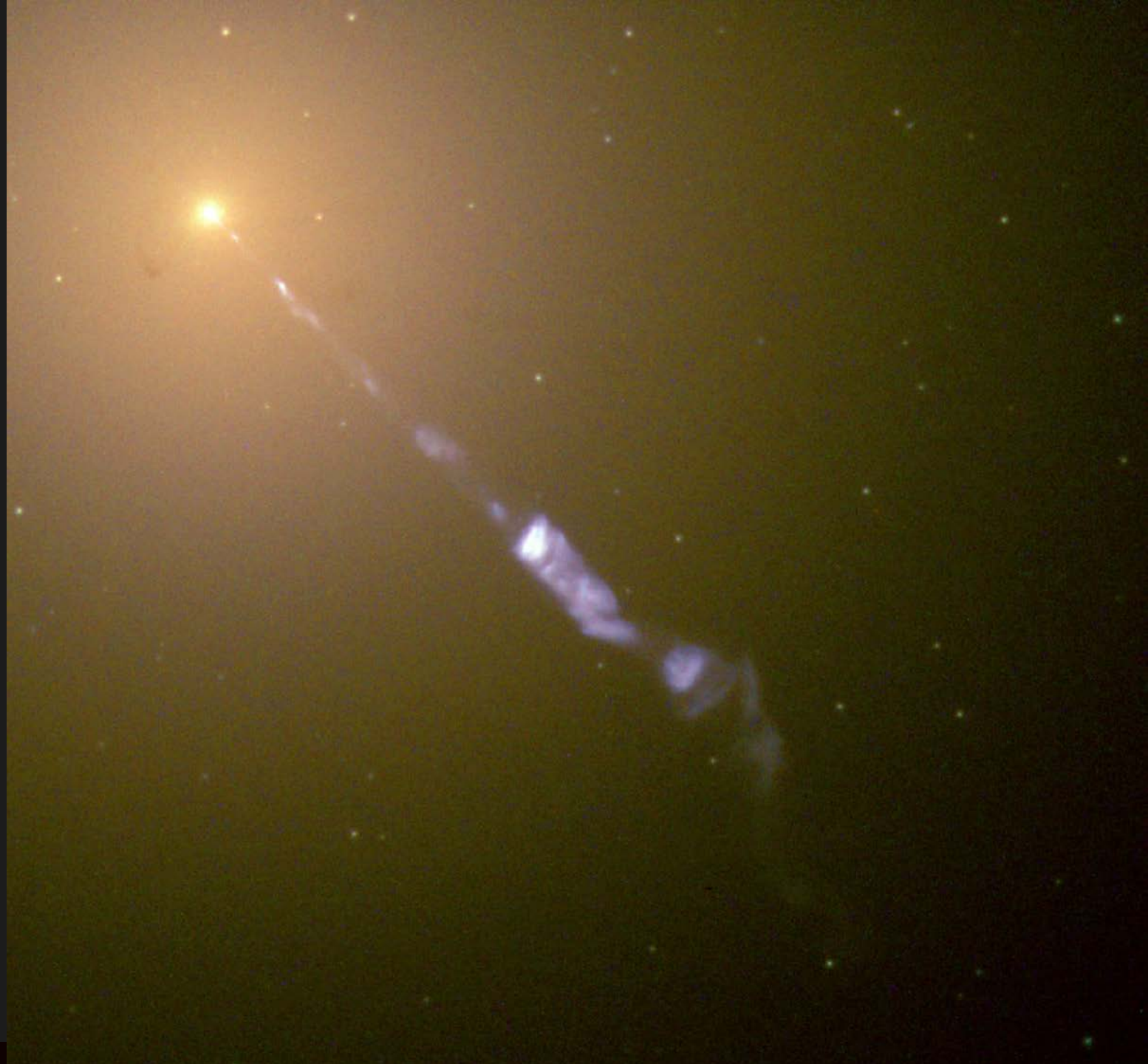

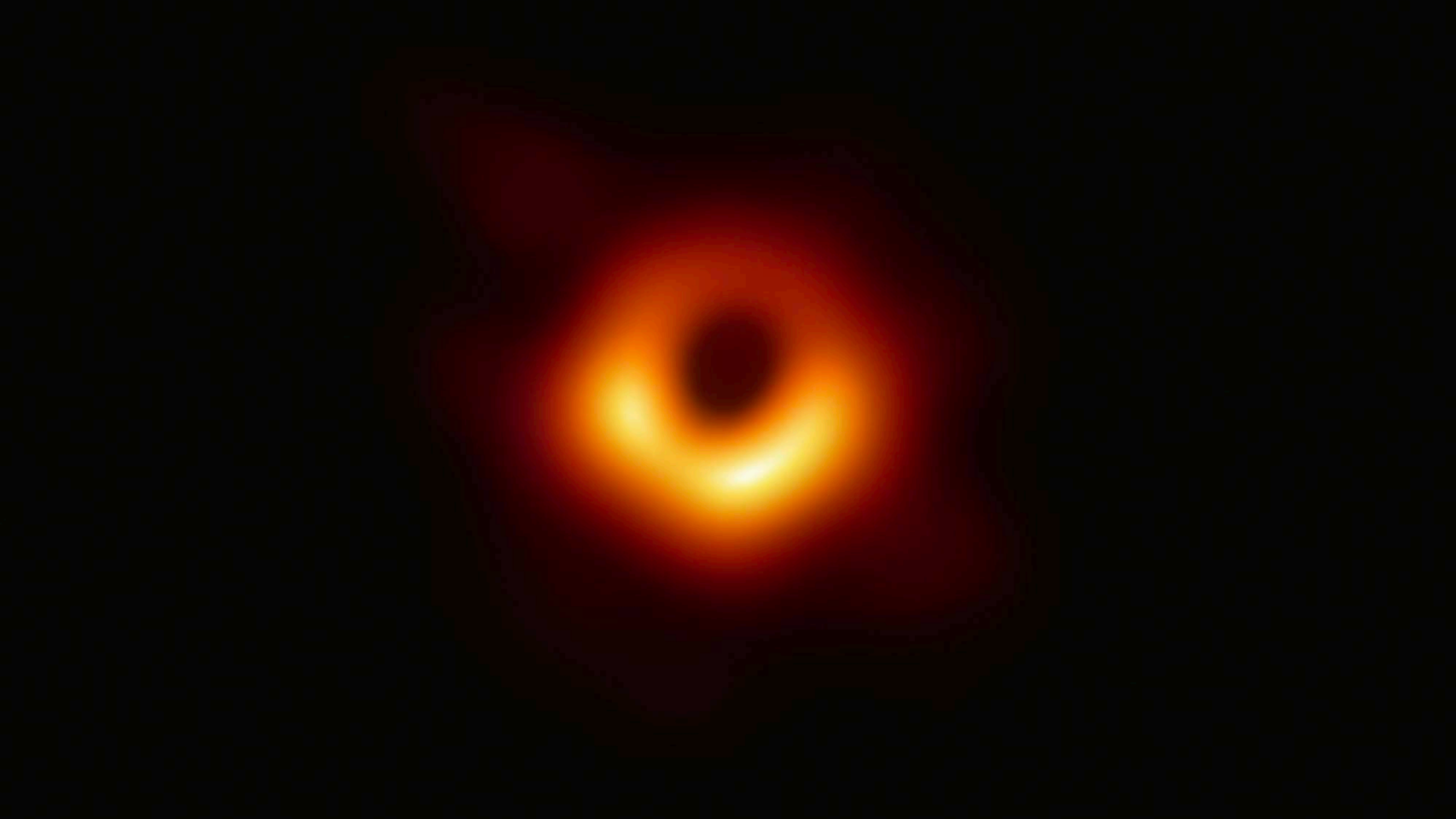

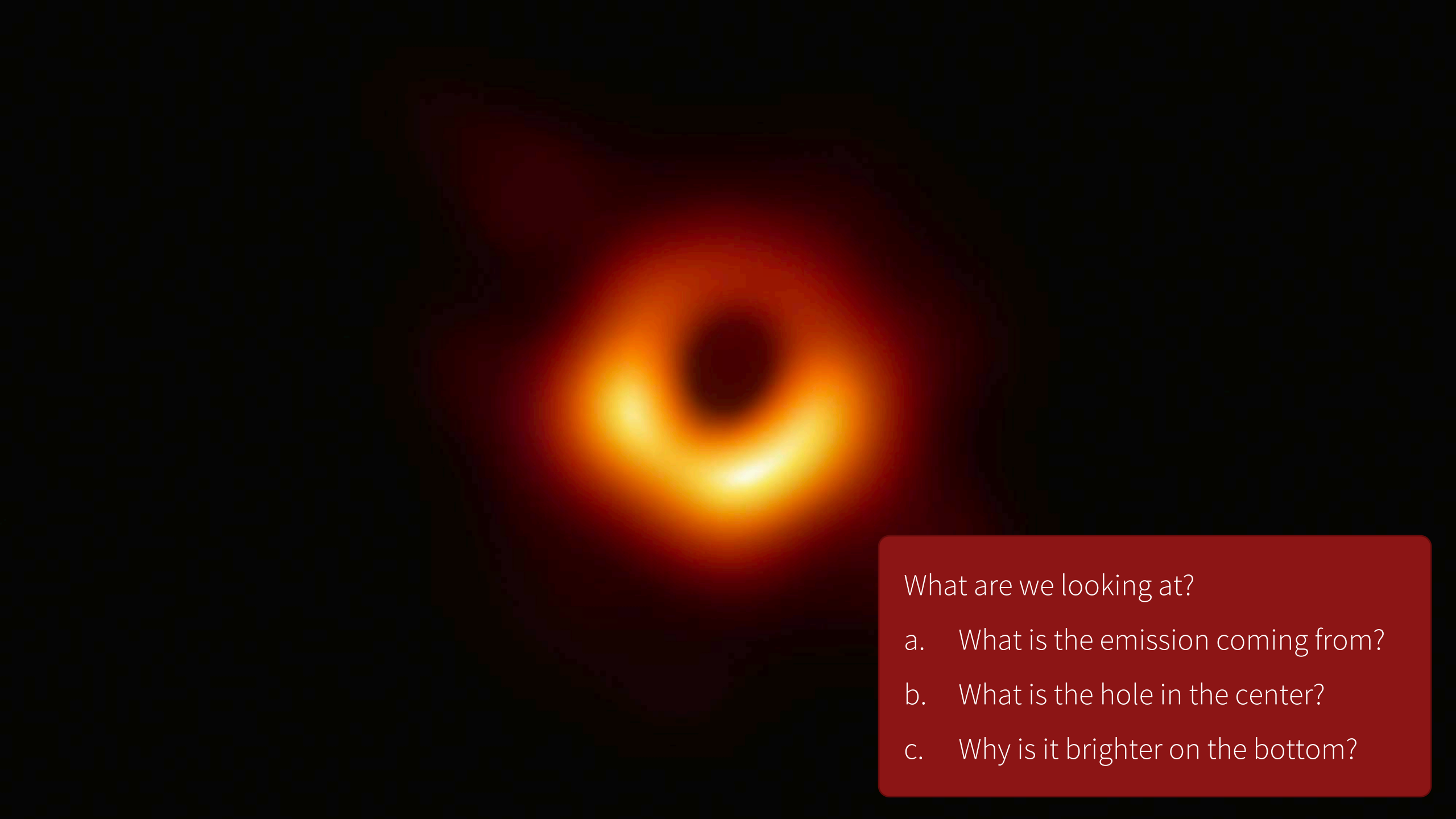

What are we looking at?

a. What is the emission coming from?

b. What is the hole in the center?

c. Why is it brighter on the bottom?

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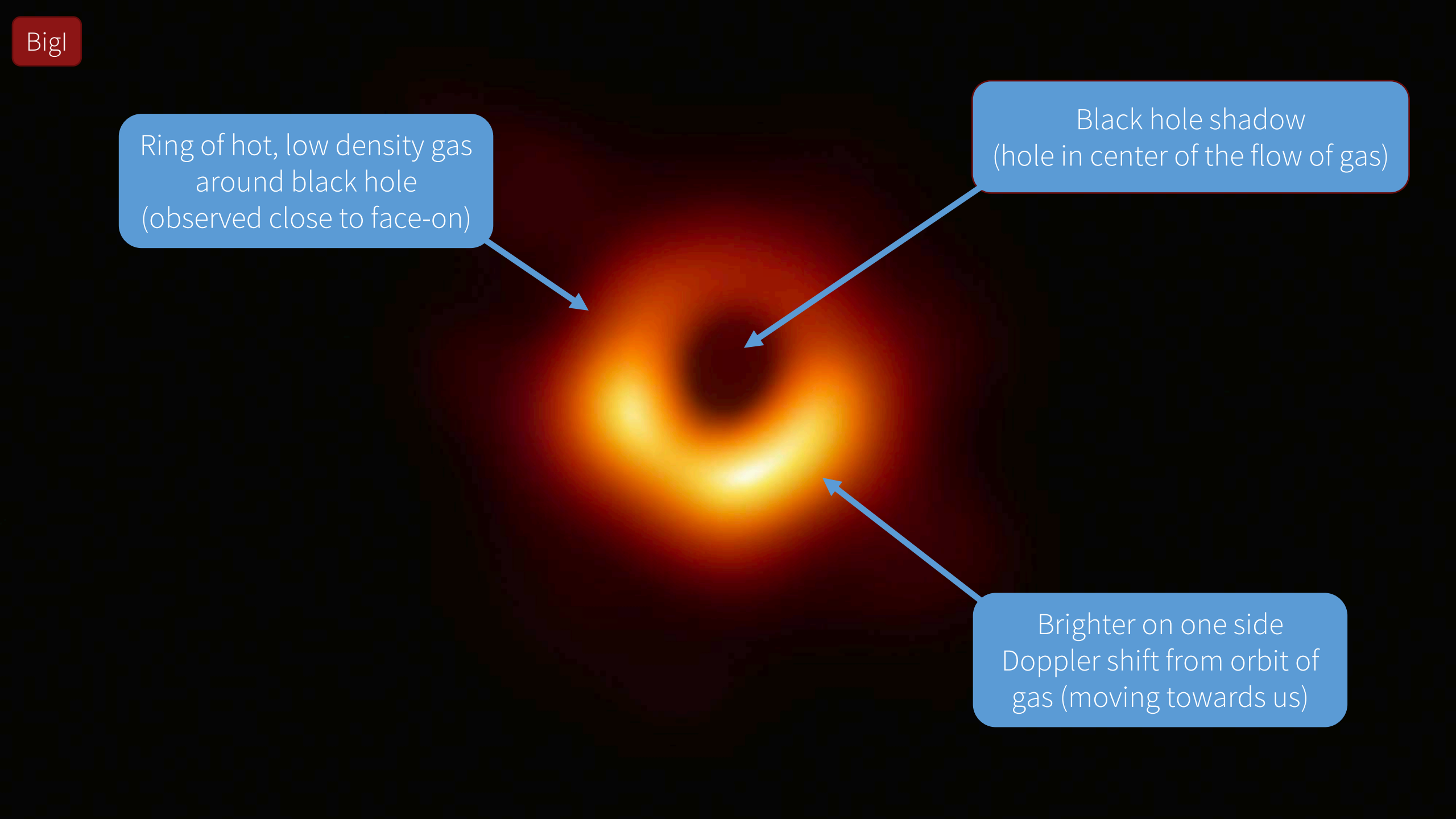
Ring of hot, low density gas around black hole (observed close to face-on)
Black hole shadow (hole in center of the flow of gas)
Brighter on one side Doppler shift from orbit of gas (moving towards us)

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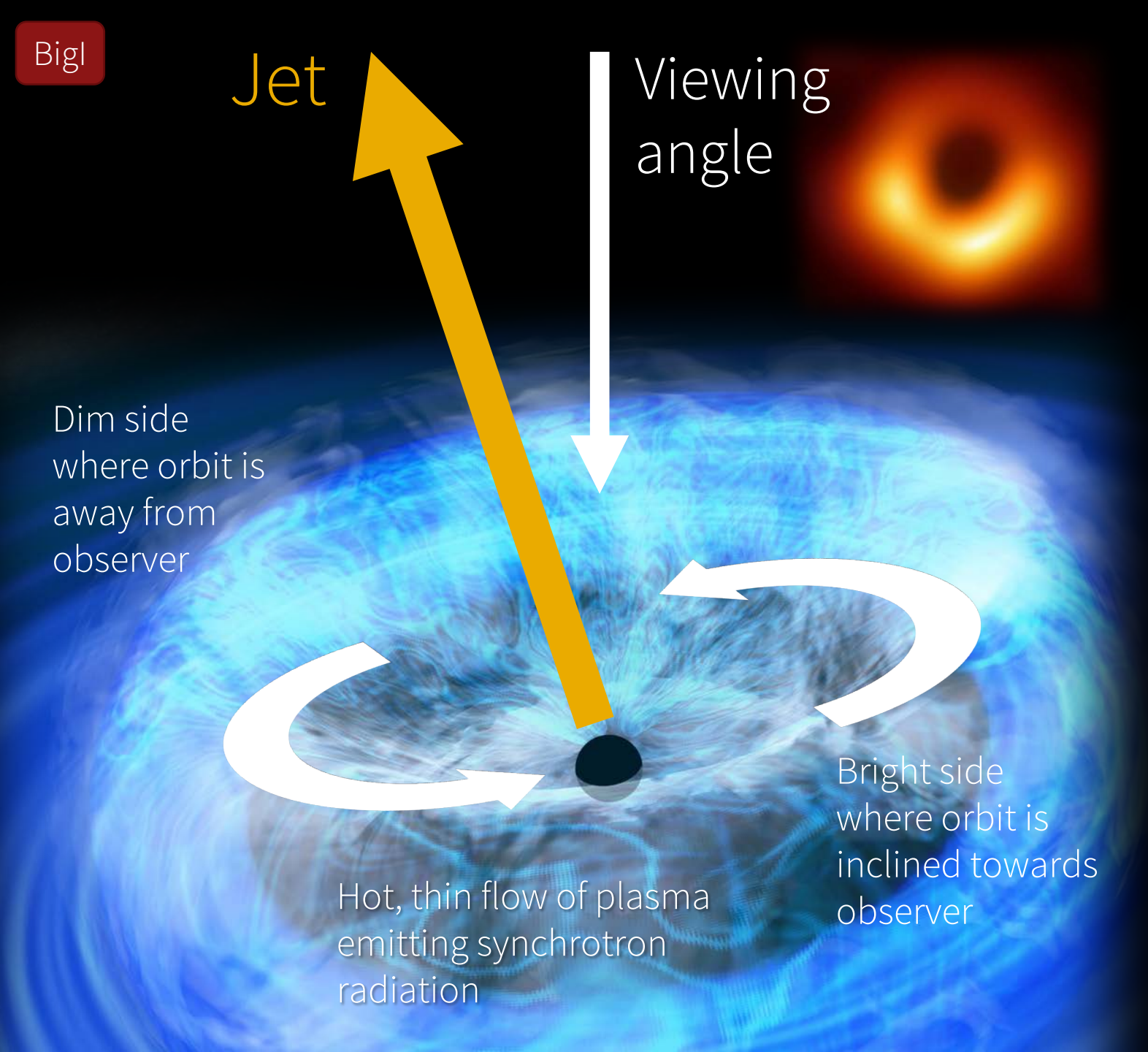
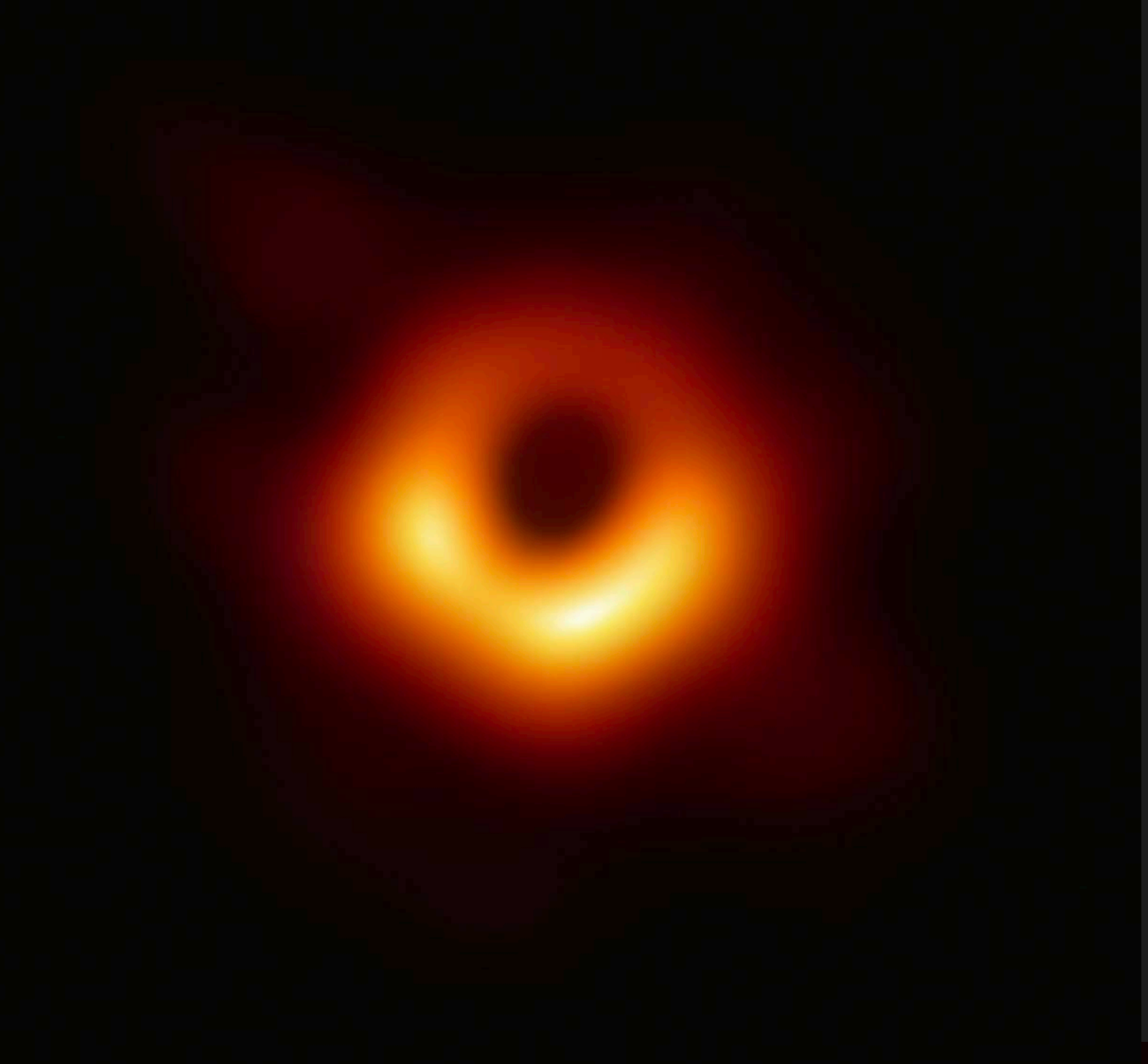

Jet
Viewing angle
Dim side where orbit is away from observer
Bright side where orbit is inclined towards observer
Hot, thin flow of plasma emitting synchrotron radiation

In M87, the Event Horizon Telescope detects synchrotron radiation from hot, low density plasma, threaded by magnetic fields, **accreting at a low rate** onto the black hole

Brightening of the lower half of the ring due to Doppler shifts. Bright part of the ring is travelling towards us in orbit. From brightening, we can determine the angle between the orbit and our viewing angle

When the plasma is thin, the light that is emitted is not absorbed. The light paths that bend around the black hole (and orbit the black hole) transmit a lot of light, emitted by all the plasma that they pass through



Putting Einstein to the Test

- First direct detection of the shadow of the event horizon, the region predicted to exist around black holes from which nothing can escape
- The size and shape of the shadow is predicted exactly by General Relativity — black holes have only 2 properties — mass and spin — can test if this is correct

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- Gravitational lensing
- Photon orbits
- Resolution of telescope is limited by its diameter
- Interferometry — combining radio waves observed by many telescopes for high resolution
- Event Horizon Telescope — interferometry on the scale of the Earth to resolve the event horizon of supermassive black holes
- Observation of black hole shadow